# *s*-Process Nucleosynthesis in Low-Metallicity Stars

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We have made a parametric study of *s*-process nucleosynthesis in the metal poor ([Fe/H] $= -2.7$) stars LP625-44 and LP706-7. We find that a high neutron exposure and a small overlap factor are necessary to fit the abundance pattern observed in these two metal-deficient stars, particularly the abundance ratios, Pb/Ba $\approx 1$ and Ba/Sr $\approx 10$. We have also constructed stellar models to better understand how such $s$-process conditions could arise. We have calculated a $2M_\odot$ model star with metallicity [Fe/H] $= -2.7$ from the ZAMS up to AGB phase. We find that for such low-metallicity stars the He convective shell reaches the bottom of the overlying H-rich envelope at the second thermal pulse. Protons are then carried into the hotter He burning layers and $^{13}$C is formed as protons mix into the He shell. Subsequently, material in the H-flash driven convective zone experiences a high neutron exposure due to the $^{13}$C($\alpha$, n) reaction. This results in a new neutron-capture *s*-process paradigm in which the abundances are characterized by only one neutron exposure. We suggest that this new *s*-process site may be a significant contributor to the *s*-process abundances in low-metallicity ([Fe/H] $\leq -2.5$) stars.

***KEYWORDS:*** ***s-process, AGB stars, lead, nuclear reactions***

## I. Introduction

One of the important mechanisms by which heavy elements are produced in Nature is the slow neutron capture process (*s*-process). In the *s*-process, the typical neutron capture timescale is longer than the beta-decay timescale. Thus, heavy element synthesis from iron peak nuclei proceeds along beta stability line and finally reaches lead (Pb) and bismuth.

An extensive survey of metal deficient stars in the Galactic Halo has recently been completed.[1)] One of the most exciting discoveries to emerge from this survey is that many stars show enhancements of neutron capture element.[2,3)] Of particular relevance to this paper is a recently reported detailed abundance analysis of LP625-44 and LP706-7 by Aoki *et al.*[4,5)] These stars have almost identical metallicity as [Fe/H] $\sim -2.7$. However, unlike most metal deficient stars, these two stars appear to have an almost pure *s*-process abundance distribution. The LP625-44 star is observed to be in a binary system. Thus, this star probably experiences mass transfer from a companion star during its asymptotic giant branch (AGB) phase. By now, the companion star has evolved into a white dwarf and can not be observed directly.

Regarding the $s$-process, it is of particular interest to study the $s$-process abundances in metal-poor stars. It is now commonly accepted that $^{13}$C($\alpha$, n)$^{16}$O is the dominant major neutron source reaction in low mass AGB stars. This reaction operates at temperatures greater than $9 \times 10^7$K. Therefore, $^{13}$C burns radiatively in a narrow region at the top of the He intershell layer during a long interpulse phase near $\sim 10^4 - 10^5$ yr.[6)]

Naively, one expects that the $^{13}$C abundance produced in a star should be independent of its metallicity. This is because $^{13}$C is produced by proton capture on newly synthesized $^{12}$C. Furthermore, since the abundance of seed nuclei is low, it is expected that these stars should show an abundance distribution characterized by many neutron captures per seed. Accordingly, theoretical model calculations made before the observations of these two stars predicted Pb/Ba $> 100$ and Ba/Sr $\sim 1$ at [Fe/H] $= -2.7$.[7)]

LP625-44 and LP706-7 show, however, a peculiar distribution of *s*-process elements. In particular, Pb/Ba $\sim 1$ and Ba/Sr $\sim 10$.[4,5)] These large differences between observation and theoretical prediction may indicate that the most popular current interpretation[7)] of the nature of the $s$-process in metal-deficient AGB stars is not enough. Although Ryan *et al.*[8)] found a good fit to [Pb/Fe] and [Ba/Fe] for LP625-44, it was necessary to postulate an exceedingly low $^{13}$C abundance in order to reproduce the observation. This eliminates any predictive power of the model.

On the other hand, Fujimoto *et al.*[9)] have proposed that a new $s$-process paradigm may be at work in these low-metallicity AGB stars. In that work it was found that the He convective shell which developed during a thermal pulse could mix protons from the H-rich layer for stars with $M \leq 3M_\odot$ and [Fe/H] $\leq -2.5$. This mixing event allows the production of $^{13}$C in the He convective shell via the $^{12}$C($p$, $\gamma$)$^{13}$N($\beta^+\nu$)$^{13}$C reaction chain.

Quite recently, Van Eck *et al.*[10)] reported on abundances in three new metal-deficient stars ([Fe/H] $= -2.45, -1.7$, and $-1.65$). These stars, indeed, show an enhanced Pb abundance in comparison with other heavy elements. This is consistent with the high neutron-to-seed ratio expected in the standard theoretical model with partial mixing from H-rich convective envelope.[11)]

However, the metallicities of these three stars are larger than [Fe/H] $= -2.5$, which is the critical value for the occur-

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rence of the Fujimoto *et al.*[9] $s$-process paradigm. Thus, the Van Eck *et al.*[10] AGB stars may have evolved differently from two metal-deficient stars, LP625-44 and LP706-7. The purpose of this paper is to investigate the physical environment of the *s*-process in these two peculiar metal-deficient AGB stars.

## II. Results

### 1. Parametric Studies of *s*-Process Nucleosynthesis

We calculated *s*-process nucleosynthesis, using a schematic pulsed-neutron-source model[12] with updated neutron-capture reaction rates.[13] We assumed a fixed temperature of $10^8$ K during each neutron irradiation, consistent with $^{13}$C($\alpha$, n)$^{16}$O as the dominant reaction for the neutron production. We characterize each pulse with a constant average neutron number density ($N_n$) and a neutron exposure duration ($\Delta t$). The neutron exposure per pulse $\tau$ is defined by

$$\tau = \int N_n v_T dt \approx N_n v_T \Delta t, \qquad (1)$$

where $v_T$ is the average neutron thermal velocity. The initial abundances of seed nuclei lighter than Fe group elements are taken to be solar-system abundances scaled to a metallicity of [Fe/H] $= -2.7$. For elements heavier than the Fe group, we use solar-system r-process abundances also scaled to [Fe/H] $= -2.7$.

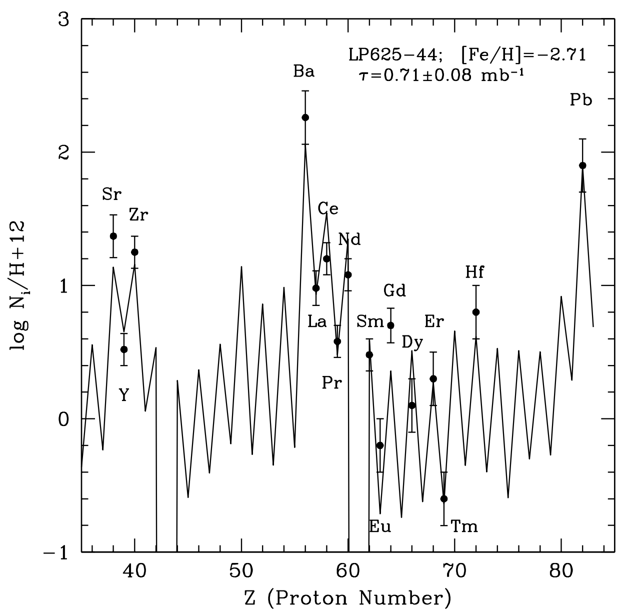


**Fig. 1** Comparison of the observed abundances of LP625-44 with the best-fit model result with a neutron exposure per pulse of $\tau = 0.71 \pm 0.08$ mb$^{-1}$.

**Figures 1** and **2** show the best fit results for LP625-44 and LP706-7, respectively. The *s*-process environment for these models is characterized by an overlap factor of $r = 0.1$, where $r$ is a fraction of material from one neutron irradiation which survives to the next neutron irradiation. The best fit neutron exposures per pulse are $\tau = 0.71 \pm 0.08$ and $0.80 \pm 0.09\,\mathrm{mb}^{-1}$

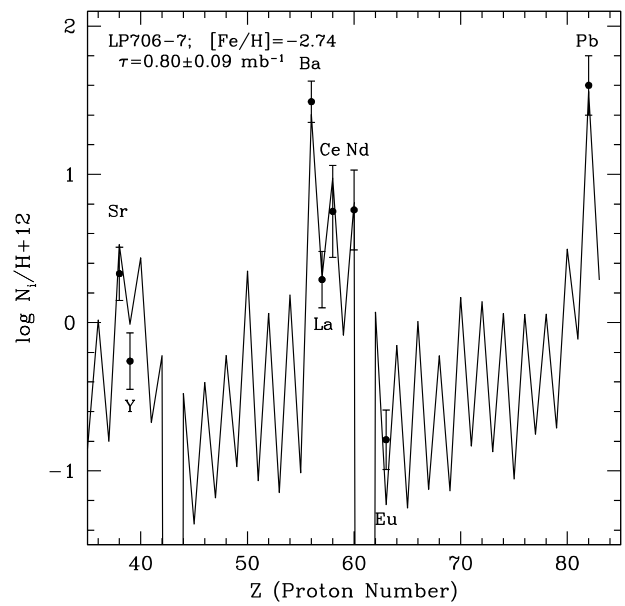


**Fig. 2** Comparison of the observed abundances of LP706-7 with the best-fit model result with a neutron exposure per pulse of $\tau = 0.80 \pm 0.09$ mb$^{-1}$.

for LP625-44 and LP706-7, respectively, corresponding to mean neutron exposures ($\tau_0 = -\tau/\ln r$) of $\tau_0 = (0.58 \pm 0.06)(T_8/3.48)^{1/2}$ and $(0.65 \pm 0.07)(T_8/3.48)^{1/2}$, respectively.

Such neutron exposures are quite high compared to parameters characterizing solar-system abundances for which the main $s$-process component is fit with $\tau_0 = (0.30 \pm 0.01)(T_8/3.48)^{1/2}$. Achieving such a high mean neutron exposure implies that very few thermal pulses could have contributed to make the *s*-process abundances for these two stars. In fact, in our model calculations, almost all elements except for Pb, are made in the first neutron irradiation with the adopted exposure. Although Pb abundance is more sensitive to the number of pulses, it too converges to its equilibrium abundance after only a few episodes. Indeed, a nearly equivalent fit to these data can be made in a model with only a single neutron exposure. However, one can not distinguish from the mean neutron exposure value whether the thermal pulse or interpulse phase site is more viable. This is because there is a degeneracy in neutron number density times irradiation time. Either site is equivalent as long as $N_n \Delta t$ gives the same neutron exposure (see the definition Eq. (1)),

### 2. *s*-Process in AGB Stars

These findings are of interest because this is exactly the behavior anticipated by Fujimoto *et al.*[9] They proposed that only a few episodes of proton mixing into the He intershell layer occur in metal-deficient stars with [Fe/H] $< -2.5$. This mixing is invoked by an upward extension of the He convective shell triggered by a thermal runaway of He shell burning. Therefore, only a few neutron exposures can be obtained. The

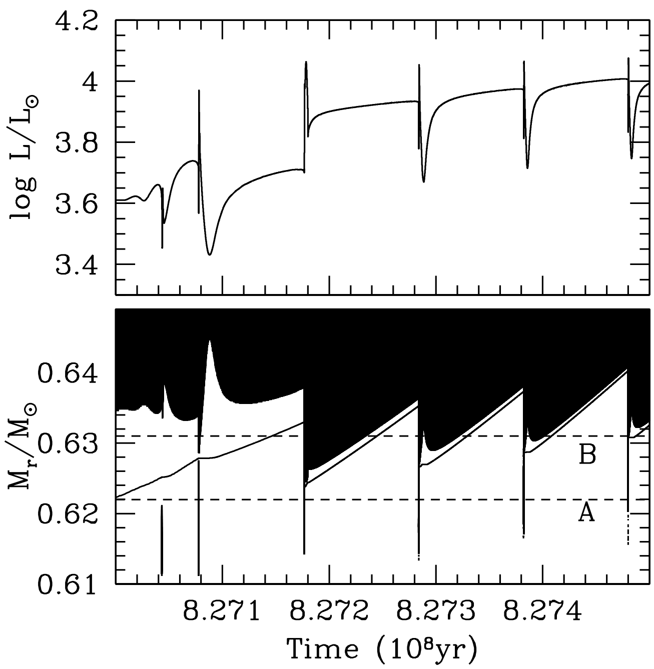


**Fig. 3** Evolution of a $2M_\odot$ stellar model on the AGB. The upper panel shows the variation of surface luminosity accompanying the thermal pulses. The lower panel shows the evolution of the internal convective zones. The shaded area denotes the envelope convective zone and the vertical lines in the He layer designate the He flash convective shell. The thick solid line indicates the H/He discontinuity. The two dashed horizontal lines shown by A and B are the mass coordinate $M_r/M_\odot = 0.622$ and 0.631, respectively.

metallicity for LP625-44 and LP706-7 ([Fe/H] $sim - 2.7$) enters exactly this metallicity range. It is thus possible that the *s*-process elements observed in these two stars are produced by this peculiar mechanism.

In the present work we have further investigated the time evolution of the He convective shell. We have calculated the stellar evolution of a $2M_\odot$ model star with [Fe/H] $= -2.7$.[14] We found that the penetration of He convective shell into the H-rich envelope takes place at the second thermal pulse and that the convective shell separates into two parts. One is sustained by H-burning and the other is sustained by He-burning (**Fig. 3**). The prompt third dredge-up then follows after the thermal runaway of both H and He burning terminates. In this way newly synthesized elements like CNO elements and lithium are brought into outer convective envelope. Thus, we see these stars as carbon-rich stars. These are usual third dredge-up events. However, as seen in Fig. 3, after the first two pulses no more proton mixing occurs although third dredge-up events continue to repeat.

Let us consider when the outward extending He convective shell penetrates into H-rich outer layer. In the He convective shell, the CN cycle operates and produces $^{13}$C and $^{14}$N from the proton capture on $^{12}$C which has been synthesized by the triple $\alpha$ reaction. Under these circumstances $^{13}$C can easily capture an alpha particle and produce neutrons via $^{13}$C($\alpha$, n)$^{16}$O. We have used the neutron exposure evaluated in this way to estimate the influence of this proton mixing on the *s*-process. We used a stellar evolution code which included all neutron capture reactions up to Si isotopes. Note that we do not introduce protons into He layer artificially (i.e., no $^{13}$C pocket is assumed). The resultant neutron exposure with time is illustrated in **Fig. 4**. The first sharp rise in neutron exposure at the second thermal pulse is due to rapid neutron production by alpha capture on $^{13}$C at both mass coordinates A and B (see Fig. 3). Inside the He convective shell (lower panel A in Fig. 4) this neutron exposure dominates over the subsequent ones. However, at the mass coordinate B (upper panel in Fig. 4) all successive neutron irradiations have a significant influence. The neutron production reaction gets activated during the interpulse phases as well as during thermal pulses, as the number of thermal pulse cycle increases.

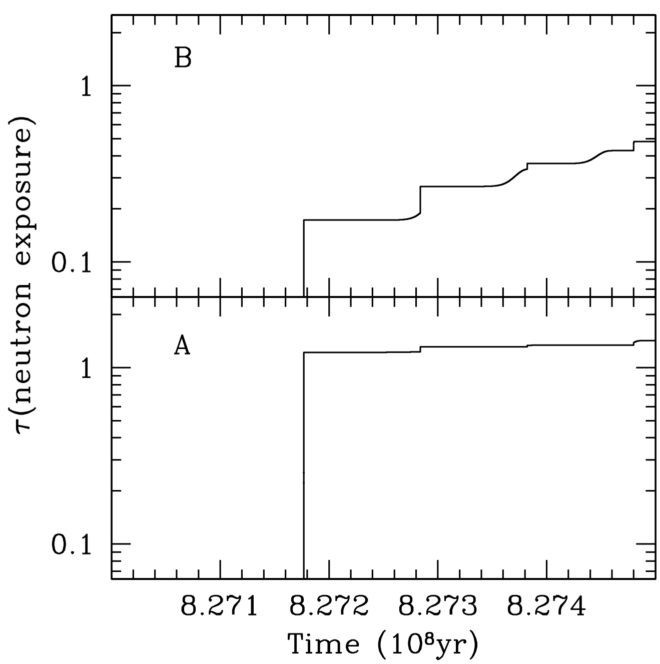


**Fig. 4** Evolution of neutron exposure at the two mass coordinates A and B as shown in Fig. 3.

## III. Conclusion and Discussions

The two metal-deficient stars, LP625-44 and LP706-7, show a strong enhancement of *s*-process elements. Therefore, the abundance ratios of Ba/Sr and Pb/Ba provide a precious opportunity to understand the *s*-process mechanism in metal-deficient AGB stars. First, we used a schematic pulsed *s*-process model to estimated the neutron exposure per pulse for these stars. We found neutron exposures $\tau \sim 0.71$ and 0.80 mb$^{-1}$ for LP625-44 and LP706-7, respectively. We recognized that these abundance ratios can be explained by high neutron number density as well as low one, which means that a true site for *s*-process, interpulse or thermal pulse, cannot be distinguished by this schematic model. Nevertheless, it seems likely that the implied high mean neutron exposures probably indicate that very few pulses contribute to the observed *s*-process abundances.

Secondly, we have calculated the evolution of $2M_\odot$ metal-deficient ([Fe/H] $= -2.7$) stars up to the AGB phase. We found that these low-mass, metal-deficient stars experience proton mixing into the He intershell convection zone. Therefore, an H-flash occurs early in the thermally pulsing AGB phase. This brings about a large change in the surface chemical composition. Significant amounts of $^{12}$C and $^{13}$C are dredged-up during a single deep convective-mixing episode. The surface composition then changes from being oxygen-rich to carbon-rich.

We have estimated the neutron exposure in the H-flash convective zone using a detailed stellar evolution model and a reaction network extending up to Si isotopes.[14] We obtained a distribution of exposures for various mass zones which can be even higher than $\tau \sim 1$ mb$^{-1}$. Thus the high neutron exposures necessary to account for s-process abundances observed in the low-metallicity stars, LP 625-44 and LP706-7,[5] are easily explained in this model.

In our stellar evolution models, material experiencing the *s*-process in the H-flash convective zone is dredged-up by the immediate penetration of the convective envelope. The *s*-process occurs in the He-flash convective shell, too. The neutron exposure in the He-flash convective shell is higher than the neutron exposure in the H-flash convective shell. The flash-driven convective shell at the next thermal pulse mixes the previously processed material within the He layer. After the thermal pulse the third dredge-up brings this material to the surface. Thus, material exposed to high neutron irradiation appears at the stellar surface. In the interpulse period $^{13}$C remains to be burnt. As the evolution proceeds, $^{13}$C is consumed rapidly in both the interpulse phase and in the next thermal pulse. The *s*-process in these conditions is, thus, somewhat complicated and we will need further investigation to fully understand the detailed abundance profiles produced in such low-mass, metal-deficient AGB stars.

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